An Introduction to the Study of COLOUR PHENOMENA

Joseph W. Lovibond

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TO

JOSEPH W. LOVIBOND

BY THE

International Juries at the St. Louis Exposition of 1904

Silver Medal Awarded for his New Colour Theory

Bronze Medal for application of Theory and Apparatus to Pathological Investigations

Bronze Medal Awarded for Theory and Apparatus to Chemical Analysis

AN INTRODUCTION TO THE STUDY

OF

COLOUR PHENOMENA

EXPLAINING

A NEW THEORY OF COLOUR
BASED ENTIRELY ON EXPERIMENTAL FACTS
WITH APPLICATIONS TO SCIENTIFIC AND
INDUSTRIAL INVESTIGATIONS

BY

JOSEPH W. LOVIBOND

ILLUSTRATED BY DIAGRAMS AND PLATES
COLOURED BY HAND

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PREFACE.

The present work is the outcome of investigations made since the publication of "The Measurement of Light and Colour Sensations" in 1893; it necessarily contains some descriptive matter which has been previously published, but in the main, consists of new work which is here consolidated into a distinctive colour theory, which is new in some respects.

The theory is illustrated by a series of geometrical figures, bringing the salient points into one harmonious whole, and has been awarded a silver medal by the International Jury of Awards at the St. Louis Exposition of 1904.

The Jury also awarded a bronze medal for the application of the theory to Dr. Oliver's Hæmoglobinometer and other pathological purposes; and a bronze medal for the estimation of carbon in steel.

The new system of colour nomenclature need not displace any arbitrary or popular colour terms, but may be used to define the limits within which such terms may be permissible.

The Colour Laboratory,
Salisbury.

LOVIBOND'S

THEORY OF COLOUR PHENOMENA.

INVESTIGATORS and colour workers have long felt the want of a power of recovering a given colour sensation, and of a colour nomenclature by which that sensation may be quantitatively described; for although the colour of a specific substance is constant under a given set of conditions, there is no recognised scale in which the sensation finds a position, nor can colour departures from it be described in other than general terms.

The work described in the following paragraphs is an attempt to supply these wants, and may be classified under seven heads.

1. The construction of a series of glass standard colour scales, which are co-related to some physical colour constants, and by means of which a colour sensation can be measured, recorded, and reproduced at will.

2. An optical instrument and apparatus for cutting off disturbing side lights and providing a set of normal conditions for making colour comparisons.

3. A system of colour development, colour nomenclature, and colour notation, capable of describing a colour sensation in quantitative terms.

4. A series of charts in one or another of which any measured colour sensation finds a position which no other can occupy.
5. A method of tabulating and illustrating by curves the rate of colour development for increasing densities of a given substance, providing a means for the future identification of similar substances.
6. Examples of application for scientific and industrial purposes.
7. The formulation of a new colour theory and a code of laws, which have been evolved out of the experimental facts.

The Glass Standard Colour Scales.

At an early period of the investigation, it was found that coloured glass gave better results than coloured solutions, and that red, yellow and blue were the only colours suitable for systematic work; it was also found that any colour could be produced by their combination. Arbitrary scales were first used in many colours, but were afterwards superseded by three colours only, which, once graded in equivalents, were found to cover all daylight colours.

Upon this evidence, scales of red, yellow, and blue were constructed of glass slips, the slips of each scale being all of one colour with a regular variation in intensity from 0·01 to 20 units, equal units of the three scales being in colour equivalence with each other, the dimensions of the unit are necessarily arbitrary, but the scales comply with the essentials of a scientific standard, in that the divisions are equal and the unit recoverable.

The equality of divisions in the scales is demonstrable by a system of cross checking.

The test of colour equivalence is that a white light, viewed through equal units of the three scales, should give no evidence of colour. The white light used for this purpose is that of a so-called sea-fog away from the contaminating influence of towns. The fogs on Salisbury Plain furnished the light actually used, and the standards of equivalence were only arrived at after two years' observation by a staff of trained observers.

The power of recovering the unit is by co-relating them with well-known physical colour constants, such as are easily obtained by definite thicknesses of solutions of given percentage of selected pure chemical compounds in distilled water at standard temperatures, for example, a 1 per cent. solution of pure crystallised copper sulphate, $CuSO_4$, $5H_2O$, at 60° F. when viewed in the tintometer in a 1-inch cell must be matched by the following combination of glasses.

Yellow		Blue
0·58	and	1·85

The 1-inch distilled water itself constitutes very little of this colour, the colour of distilled water is remarkably uniform, and might be almost taken as a colour constant, thus :—

A 2-foot stratum	is matched by	0·10	yellow	and	0·34	blue
A 4-foot	,,	,,	1·0	,,	1·45	,,

Nickel sulphate, $NiSO_4$, $7H_2O$. Temp. 60° F.

A 1 per cent. solution in a 2 inch stratum must be matched by 2·2 blue and 2·0 yellow units.

Potassium bichromate, K_2Cr_2O. Temp. 60° F.

A 1 per cent. solution in a 2-inch stratum, after being dulled by 0·5 neutral tint, must be matched by 34 yellow and 9·6 red units.

Copper sulphate, $CuSO_4$, $5H_2O$. Temp. 60° F.

A 1 per cent. solution in a 2-inch stratum, after being dulled by 0·1 neutral tint, must be matched by 1·1 yellow and 3·4 blue units.

A Description of the Optical Instrument and Apparatus.

The Instrument,

Which is illustrated by Fig. 1, consists essentially of a double tube, ending in an eye-piece at one end, and in equal

Fig. 1.

apertures for viewing the colour to be measured, and the glasses used as measures, at the other end.

Fig. 1 illustrates the monocular form, now only used for

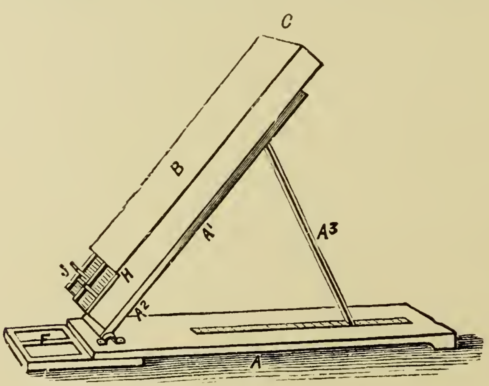


Fig. 2.

cells of greater depth than 2 inches. For general work an improved form is now preferable. This may be used either as a monocular, or as a binocular, and is illustrated in Fig. 2.

Fig. 2 shows the arrangement for measuring colour in opaque objects. The optical instrument B fits into the shoe at A, the bottom of which is commanded by both tubes of one instrument. Under one side at F is placed the opaque substance to be measured, and under the other, the standard white, for reflecting the beam of white light, which is then dissected at J by the suitable standard glasses.

Fig. 3 represents the instrument as arranged on the cover of the box for measuring colours in liquids up to 2 inches in thickness. The instrument E slides into the upright stand

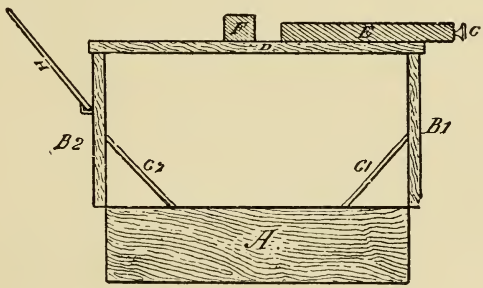


Fig. 3.

D, which fits into the two halves of the cover of the box B¹ B², these being retained in position by the springs C¹ C². If the light is obtained from a high window, the reflector H must be fitted into the cover B, and the box placed so that both the openings are equally illuminated on looking through the eye-piece G. If the light is obtained from a low window, the reflector H is not required, but instead place a piece of white tissue paper smoothly on the window, and then place the box in such a position that the two openings are equally illu minated on looking through the eye-piece G.

A separate stand is required for cells which are longer than 2 inches. The method of arrangement is shown in Fig.

4, where one end of the cell rests on the stand A, which also carries the optical instrument B, whilst the other is supported by a separate stand F, which can be moved to accommodate a tube of any length. The reflector D is supported on a separate stand.

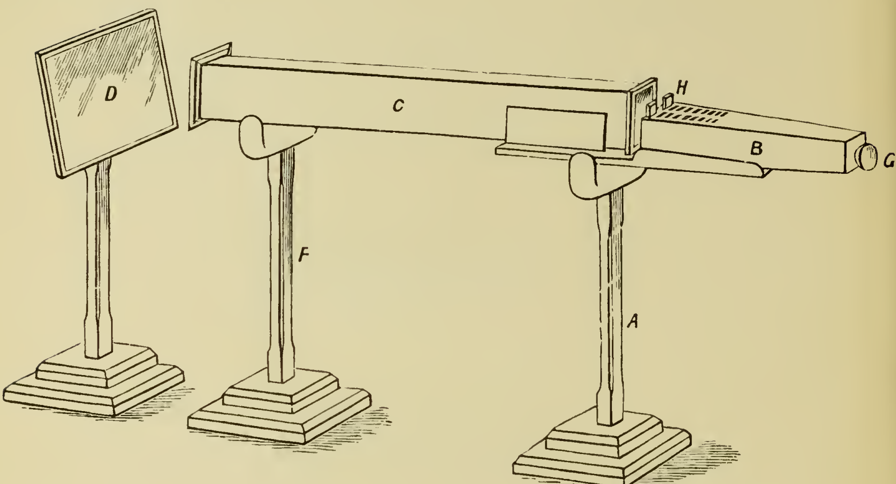


Fig. 4.—Monocular Instrument, with Long Gauged Trough and White Reflector; for Water and Similar Pale Liquids.

The instrument, in all its forms, is of extreme simplicity, a quality only arrived at after the careful testing of (literally) many hundreds of variations and suggestions, made by interested workers and others, with a view to rendering the instrument more universally useful.

Instructions for Using the Instrument.

The instrument must be placed facing the light; any ordinary daylight will do, but a north light is preferable. Direct sunlight must not be used. Then adjust the instrument so that equal quantities of light pass up each tube.

This is effected by placing a piece of paper, or some evenly-coloured surface, or, preferably, a slip of mirror-glass, under both tubes, and slightly turning the instrument towards the light until both fields of view are evenly illuminated. When this is effected, either side can be used for the standard white without affecting the measurement.

The coloured light from the object to be measured is transmitted through one tube, and the light from a standard white

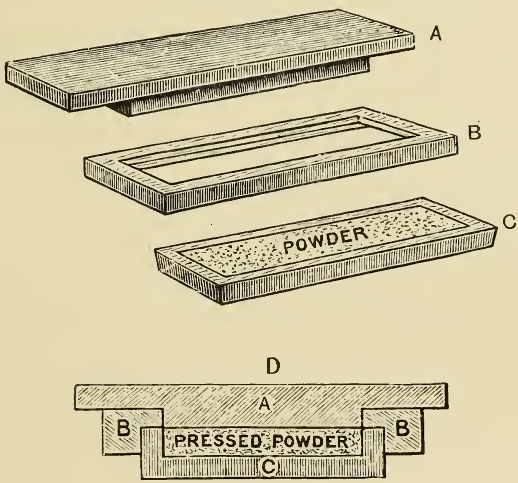


Fig. 5.

through the other, this standard white light is then intercepted by the graded coloured glasses, until it corresponds in colour with the object to be measured, when the numerical colour value of the glasses can be read off.

The standard white is pure precipitated lime sulphate, pressed evenly into a tray. In order to ensure uniformity of pressure, the following apparatus is designed for pressing two volumes into one.

A represents two pieces of glass, one larger than the other, cemented together, the smaller piece fitting into B, which is

a rectangular frame one-tenth of an inch deep; this fits into a tray C, also one-tenth of an inch deep. These are fitted together, then filled with the standard white and struck evenly off; the powder is pressed lightly down with the small side of the glass presser, in order to remove the frame B more easily from the tray C. The broad side of the presser is used to compress the powder even with the sides of the tray. The whole arrangement is shown in section at D.

If the substance is a yarn, it should be wound evenly on a flat block; if cloth or paper, pinned evenly to a block; if in powder, pressed evenly into one of the special trays.

When a liquid has to be measured, it should be poured into one of the gauged cells, or the capillary film apparatus filled with it.

The Standard Light.

The glass standards are graded for use in diffused daylight, which is found to give uniform results within the range of sixteen to twenty-eight units of luminous intensity, this being the average variation between winter and summer diffused daylight when reflected from a white surface. When lights are more intense than twenty-eight they are not sufficiently diffused, and give different results which vary with the varying intensity, and when less than sixteen units they are too low for critical discrimination.

Opaque colours are measured according to their departures from diffused daylight reflected from a smooth surface of pure precipitated lime sulphate.

For transparent colours the light may be taken from a matted surface of opal placed at a low angle in relation to the impinging light, or from a thin sheet of the whitest tissue paper placed against a north window. Care must be taken that the reflectors are within the full influence of the daylight, as the broken light of the interior has a disturbing effect.

The Method of Developing, Measuring and Naming Colour.

The single sensation colours, red, yellow and blue, are matchable by a single glass from the corresponding colour scale; the depth of colour is directly indicated by the unit value of the glass used.

The single sensation colours, orange, green and violet, are matchable by a combination of equal units from two of the standard scales; the depth of the colour is directly indicated on either of the glasses used, thus—

2 blue + 2 red develop two units violet.

A given neutral grey is matchable by a combination of equal units from the three standard scales; the depth of grey is directly indicated by the unit value on either of the glasses used, thus—

3 red + 3 yellow + 3 blue develop three units neutral tint.

The complex colour sensations, red and yellow oranges, yellow and blue greens, blue and red violets, are matchable by unequal glasses from two of the standard scales; the colour developed is not directly indicated by the unit values of the glasses, but is recorded by means of an equation, the first half of which contains the separate values of the glasses used, and the second half the names and the depth of the colour they transmit.

For instance, a 24 per cent. solution of manganese steel was matched by 17 red and 2·6 blue units, the equation is as follows :—

Standard Glasses			Colour Developed		
Red		Blue		Violet		Red
17	+	2·6	=	2·6	+	14·4

The colour developed is a red violet in these proportions.

A colour matched by

Standard Glasses			Colour Developed	
Red	Yellow		Red	Orange
10 +	3	=	7 +	3

The colour developed is a red orange in these proportions.

A colour matched by

Standard Glasses			Colour Developed	
Yellow	Blue		Yellow	Green
3 +	1·5	=	1·5 +	1·5

The colour developed is a yellow green in these proportions.

A colour matched by

Standard Glasses			Colour Developed	
Blue	Red		Blue	Violet
6 +	1·8	=	4·2 +	1·8

The colour developed is a blue violet in these proportions.

The glass colours are necessarily of a given brightness, and colours for measurement may be either brighter or sadder than the standards.

A given complex colour of less than glass standard brightness is matchable by unequal glasses from the three standard scales, the equation is as follows: the smallest unit value always represents the "black" or neutral tint factor.

A colour matched by

Standard Glasses				Colour Developed		
Red	Yellow	Blue		Neutral Tint	Blue	Green
1·0 +	3·0 +	9·0	=	1·0 +	6·0 +	2·0

The colour is a blue green in the proportion of 6·0 to 2·0 saddened by 1·0 of neutral tint.

A given complex colour of greater brightness than the glass standards is first dulled by the interception of neutral tint units until measurable in the manner described above;

the intercepting glasses represent the unit value of excess of brightness, and shown in the equation as light units, for instance.

A colour dulled by

Standard Glasses				Colour Developed		
Neutral Tint	Yellow	Blue		Yellow	Green	Light
1·5 =	7·5 +	0·5	=	7·0 +	0·5 +	1·5

The colour is a yellow green in the proportions of 7·0 to 0 5 and 1·5 units of light brighter than standards.

Every daylight colour being thus measurable by a suitable combination of standard glasses with or without an addition of a light or neutral tint factor, it follows that any colour can be described both qualitatively and quantitatively in terms of the colour sensations yielded by the standard glasses and their combination. The distinct colour sensations are those which by common consent are known as red, yellow, blue, orange, green and violet, and they are yielded by single glasses or by pairs of glasses, as already described ; all colours therefore fall into the following categories.

A.—Single colour sensations.

1. Transmitted by single standard glasses—

    Red
    Yellow
    Blue.

2. Transmitted by equivalent pair of standard glasses—

    Orange
    Green
    Violet.

B.—Double sensation colour transmitted by unequal pairs of standard glasses.

Red orange transmitted by unequal units of red and yellow, red preponderating.

Yellow orange transmitted by unequal units of red and yellow, yellow preponderating.

Yellow green transmitted by unequal units of yellow and blue, yellow preponderating.

Blue green transmitted by unequal units of yellow and blue, blue preponderating.

Blue violet transmitted by unequal units of blue and red, blue preponderating.

Red violet transmitted by unequal units of blue and red, red preponderating.

C.—Any of the above colours with the addition or subtraction of neutral tint.

Neutral tint itself is transmitted by a combination of equal units of the standard glasses, thus 3 units, red, yellow and blue, when superposed, transmit 3 units neutral tint.

Any given colour is, therefore, designated qualitatively and quantitatively by the name of the colour sensation it produces, expressed in the terms of colour units together with the light factor expressed in terms of neutral tint units.

Examples.

Three units of red, of standard brightness, completely describes a colour matched by a red glass standard of three units, and is denoted

R 3.

Three units of red, saddened by one neutral tint, completely describes a colour matched by a red glass standard of four units red, combined with blue and yellow of one unit each, and is denoted

R 3 + N.T.1.

Three units of red, brighter than standards by one unit of white light, is matched by a red glass of three units after being saddened by glasses of one unit each, red, yellow and blue, is denoted

R 3 + Light 1.

Three units of violet, of standard brightness, is matched by a red and blue glass of three units, and is correctly described by

V 3.

Three units of orange, of standard brightness, is matched by a red and yellow glass of three units, and is correctly described by

O 3.

A binary red violet, of standard brightness, in which red preponderates by one unit, is matched by a red of four units and a blue of three units, and is correctly described by

R 1 + V 3.

A binary red orange, of standard brightness, in which orange preponderates, is matched by red four and yellow three units, and is correctly described by

R 1 + O 3.

A red violet, of less than standard brightness by one unit, in which red preponderates by one unit, is matched by red 5, blue 4 and yellow 1, and is correctly described by

R 1 + V 3 + N.T. 1.

A red orange, of less than standard brightness by one unit, in which orange preponderates by one unit, is matched by a red 5, yellow 4, blue 1, and is correctly described by

R 1 + O 3 + N.T. 1.

A red violet, in which red preponderates by one unit, and is one unit brighter than standard, is first dulled by 1 red, yellow and blue, and then matched by 4 red and 3 blue, and is correctly described by

R 1 + V 3 + Light 1.

A red orange, in which red preponderates by one unit, and is one unit brighter than standard, is first dulled by 1 red, yellow and blue, and then matched by 4 red, 3 yellow, and is correctly described by

R 1 + O 3 + Light 1.

The Colour Charts.

Any given colour can be charted in exact accordance with its quantitative description as above obtained.

A colour chart is constructed by placing two colour scales at right angles to each other on section paper as shown. A pure colour finds a position directly on a corresponding colour line, and a complex colour at that point within the angle, where perpendiculars drawn through the unit values of each colour meet, the unit value of the light factor (if any) is written in numerals as light or black near the charted point. It is sometimes more convenient to make the charts double, placing the colours brighter than standards on the left of the perpendicular and those less bright on the right. Any colour sensation measured in diffused daylight finds a position on one or another of the following six charts illustrated in Plate I.

Specific Colour Development.

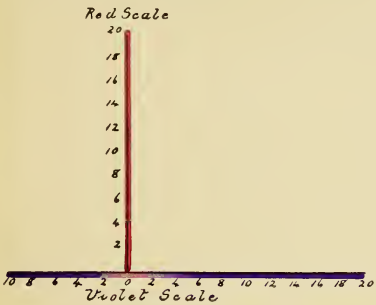
The question of the rate of colour development for regularly increasing densities has been an obscure one in the past, but the measurement of a number of substances of

PLATE I.

SIX COLOUR CHARTS IN ONE OR ANOTHER OF WHICH ANY SIMPLE OR COMPLEX COLOUR FINDS A DEFINITE POSITION.

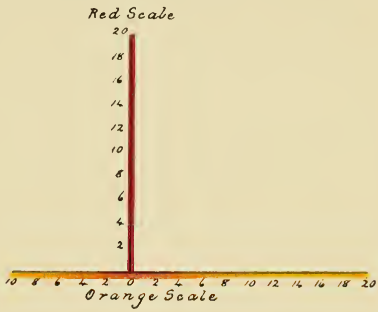
No. 1.

RED VIOLET CHART.



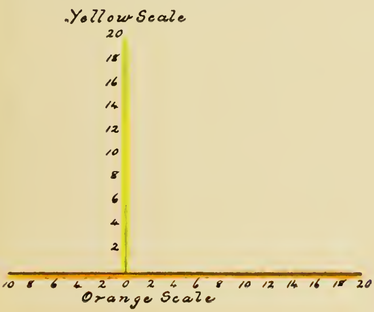
No 2

RED ORANGE CHART



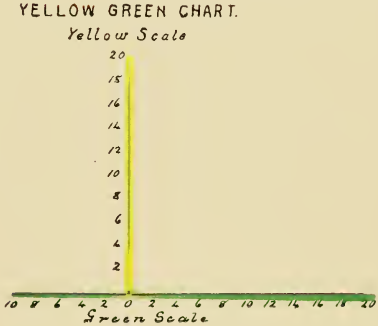
No. 3.

YELLOW ORANGE CHART



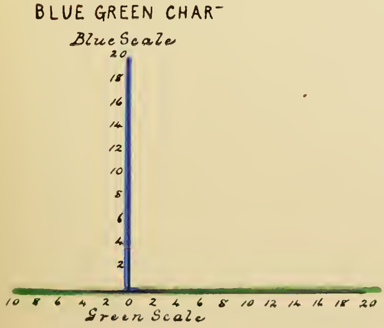
No. 4.

YELLOW GREEN CHART.



No. 5.

BLUE GREEN CHART



No. 6.

BLUE VIOLET CHART

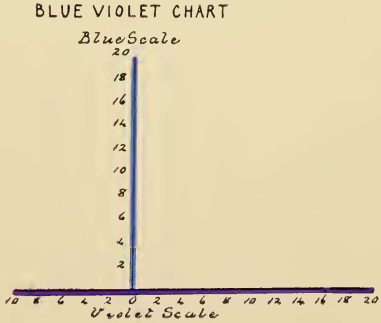
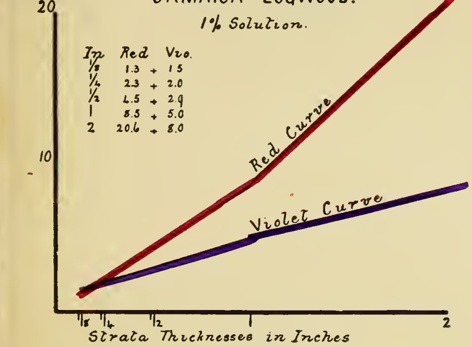


PLATE II.

ABSORPTION CURVES OF SIX DYES.

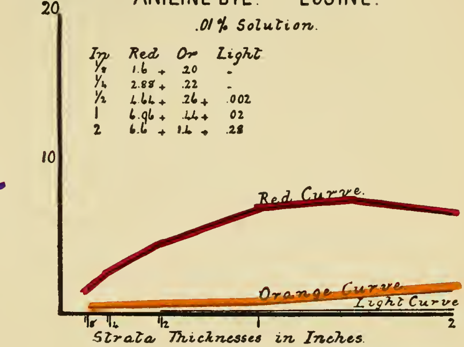
1 JAMAICA LOGWOOD.

1% Solution.



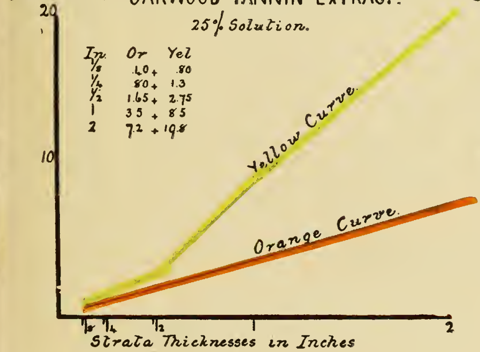
2 ANILINE DYE. EOSINE.

.01% Solution.



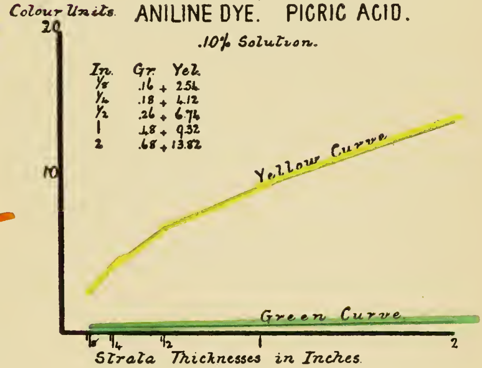
3 OAKWOOD TANNIN EXTRACT.

25% Solution.



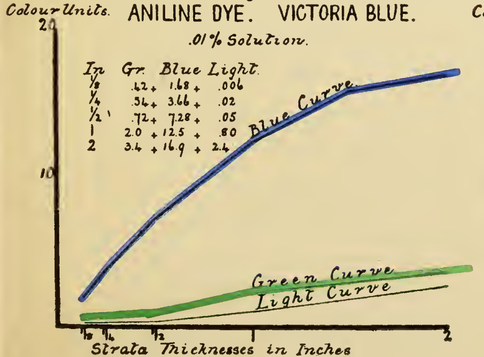
4 ANILINE DYE. PICRIC ACID.

.10% Solution.



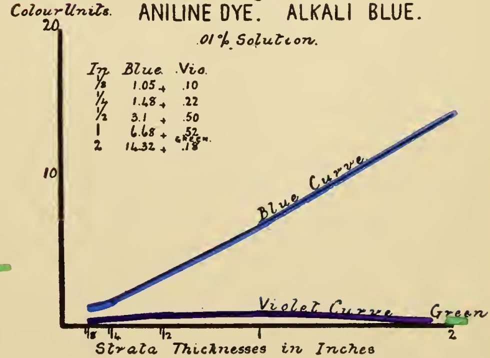
5 ANILINE DYE. VICTORIA BLUE.

.01% Solution.



6 ANILINE DYE. ALKALI BLUE.

.01% Solution.

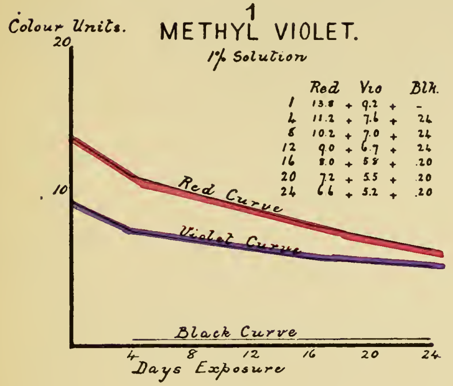


SIX ANILINE DYES.

CURVES ILLUSTRATING THE RATE OF FADING BY EXPOSURE TO LIGHT.

1 METHYL VIOLET.

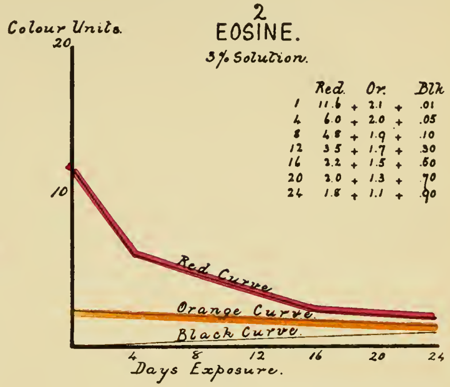
1% Solution



	Red		Vio		Blk.
1	13.8	+	9.2	+	-
4	11.2	+	7.6	+	24
8	10.2	+	7.0	+	24
12	9.0	+	6.7	+	24
16	8.0	+	5.8	+	.20
20	7.2	+	5.5	+	.20
24	6.6	+	5.2	+	.20

2 EOSINE.

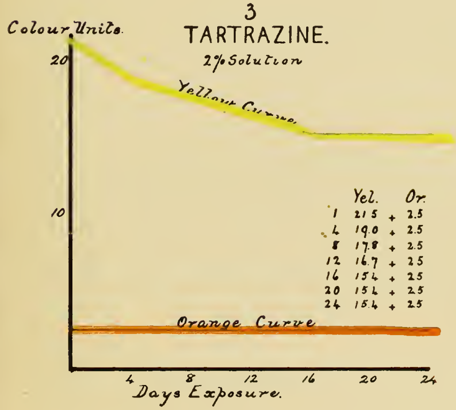
3% Solution.



	Red.		Or.		Blk
1	11.6	+	2.1	+	.01
4	6.0	+	2.0	+	.05
8	4.8	+	1.9	+	.10
12	3.5	+	1.7	+	.30
16	2.2	+	1.5	+	.60
20	2.0	+	1.3	+	.70
24	1.8	+	1.1	+	.90

3 TARTRAZINE.

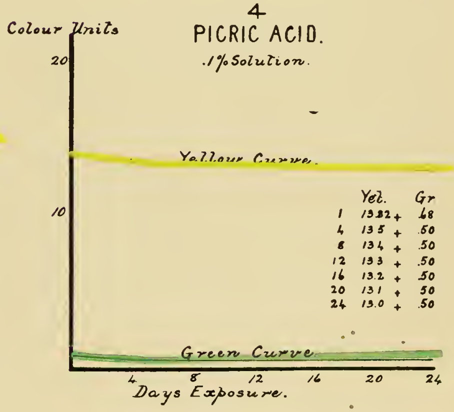
2% Solution



	Yel.		Or.
1	21.5	+	2.5
4	19.0	+	2.5
8	17.8	+	2.5
12	16.7	+	2.5
16	15.4	+	2.5
20	15.4	+	2.5
24	15.4	+	2.5

4 PICRIC ACID.

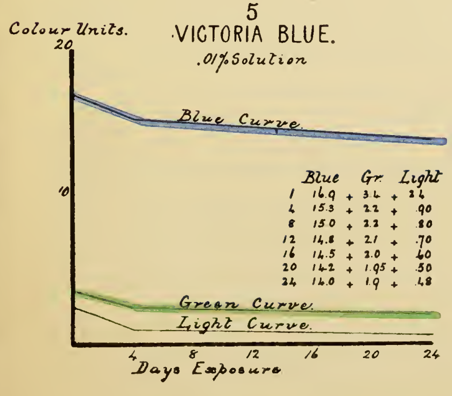
.1% Solution.



	Yel.		Gr
1	13.82	+	.48
4	13.5	+	.50
8	13.4	+	.50
12	13.3	+	.50
16	13.2	+	.50
20	13.1	+	.50
24	13.0	+	.50

5 VICTORIA BLUE.

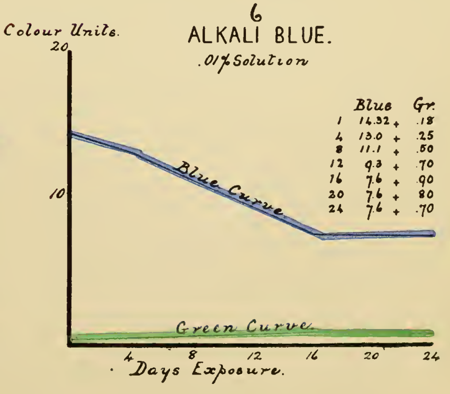
.01% Solution



	Blue		Gr.		Light
1	16.9	+	3.4	+	24
4	15.3	+	2.2	+	.90
8	15.0	+	2.2	+	.80
12	14.8	+	2.1	+	.70
16	14.5	+	2.0	+	.60
20	14.2	+	1.95	+	.50
24	14.0	+	1.9	+	.48

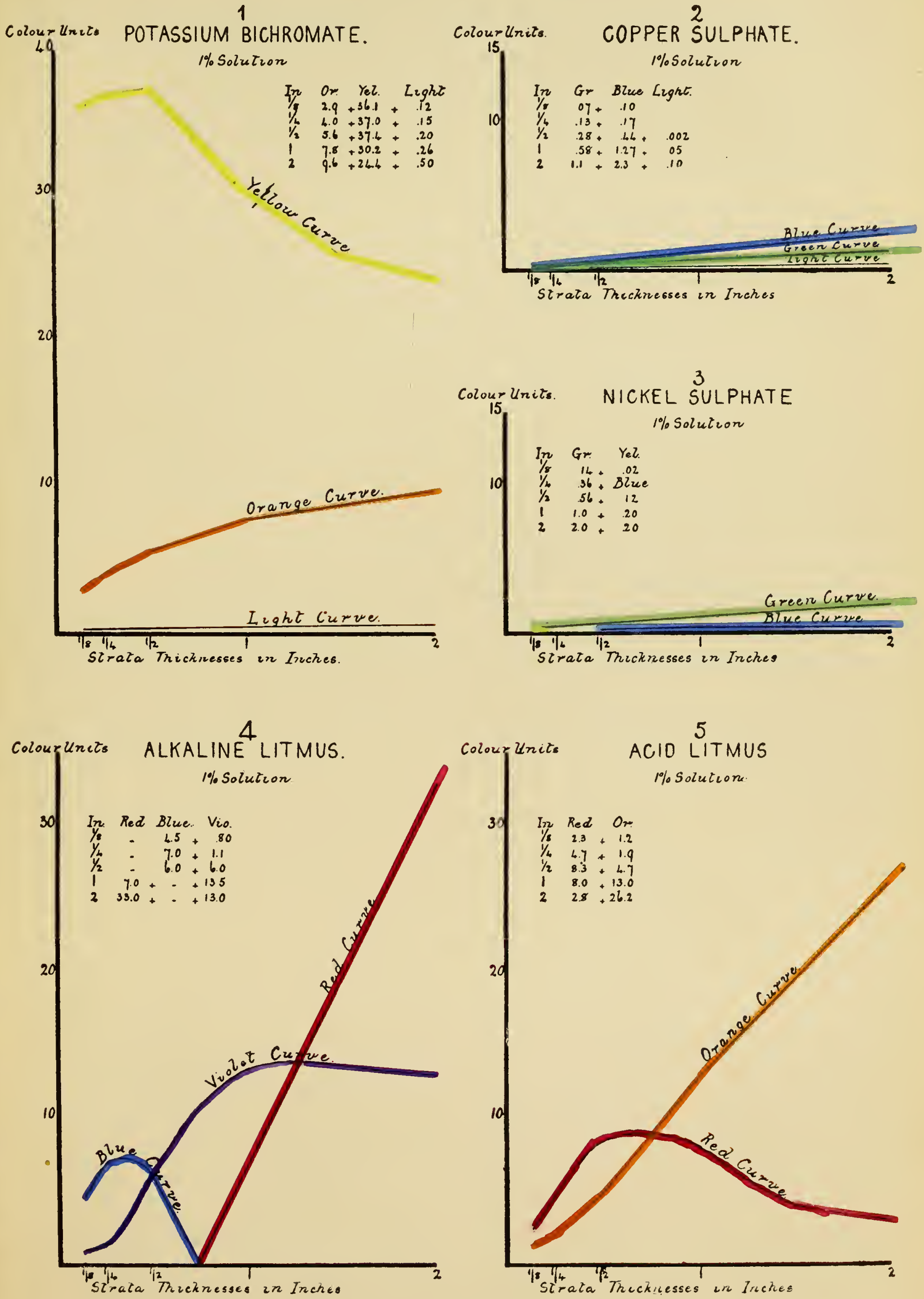
6 ALKALI BLUE.

.01% Solution



	Blue		Gr.
1	14.32	+	.18
4	13.0	+	.25
8	11.1	+	.50
12	9.3	+	.70
16	7.6	+	.90
20	7.6	+	80
24	7.6	+	.70

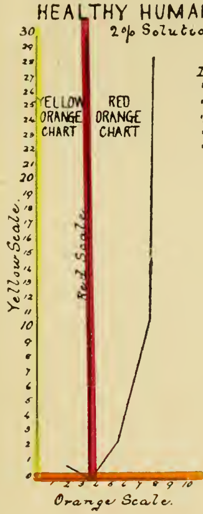
ABSORPTION CURVES OF FIVE COLOUR CONSTANTS.



COMPARISON CURVES OF HEALTHY HUMAN BLOOD WITH THE BLOOD OF LOWER ANIMALS.

1 HEALTHY HUMAN BLOOD.

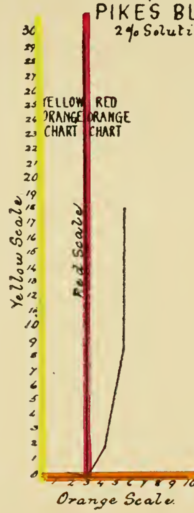
2% Solution



In	Or		Yel
1/32	20	+	red 10
1/16	37	+	20
1/8	56	+	24
1/4	76	+	104
1/2	80	+	285

2 PIKE'S BLOOD.

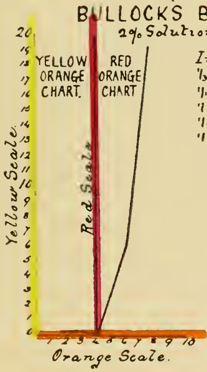
2% Solution.



In	Or		Yel
1/32	1.95	+	25
1/16	32	+	red .16
1/8	43	+	19
1/4	66	+	84
1/2	68	+	182

3 BULLOCK'S BLOOD.

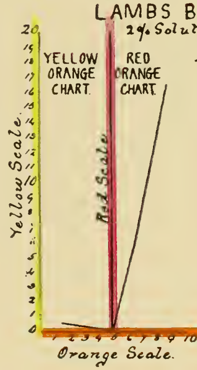
2% Solution.



In	Or		Yel
1/32	1.65	+	15
1/16	26	+	red 20
1/8	46	+	14
1/4	62	+	63
1/2	78	+	192

4 LAMB'S BLOOD.

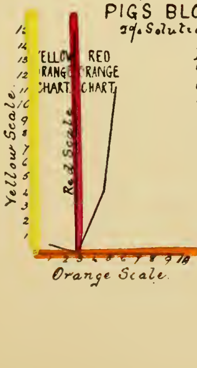
2% Solution.



In	Or		Yel
1/32	14	+	40
1/16	25	+	red 50
1/8	50	+	80
1/4	64	+	56
1/2	88	+	167

5 PIG'S BLOOD

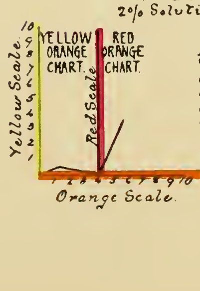
2% Solution



In	Or		Yel
1/32	10	+	50
1/16	17	+	red 40
1/8	32	+	10
1/4	48	+	42
1/2	56	+	114

6 FROG'S BLOOD.

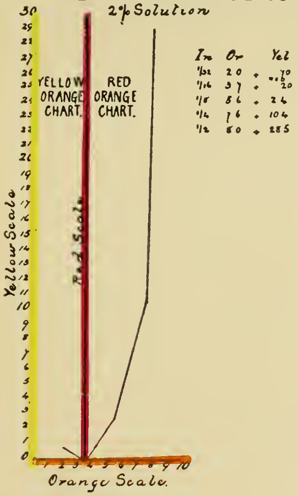
2% Solution.



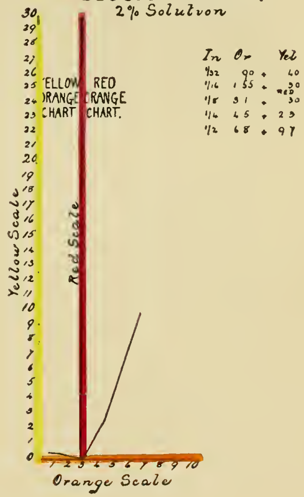
In	Or		Yel
1/32	.72	+	23
1/16	12	+	60
1/8	27	+	red 40
1/4	42	+	20
1/2	58	+	38

COMPARISON CURVES OF HEALTHY AND DISEASED BLOOD.

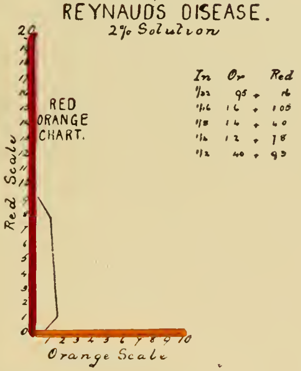
1
HEALTHY HUMAN BLOOD



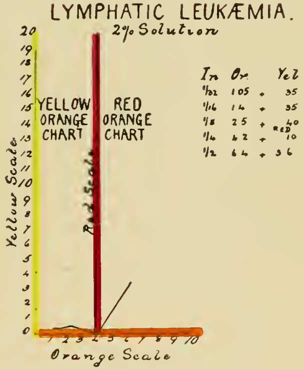
2
LEUCOCYTHÆMIA.



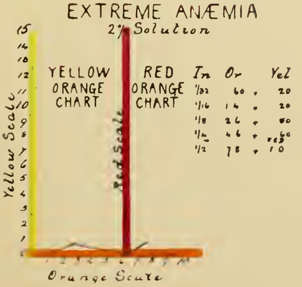
3
REYNAUD'S DISEASE.



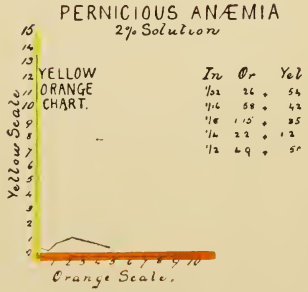
4
LYMPHATIC LEUKÆMIA.



5
EXTREME ANÆMIA



6
PERNICIOUS ANÆMIA



known composition has now demonstrated that each definite substance has its own specific rate, which may be tabulated or more graphically expressed by means of colour curves. Either method affords a ready means of identifying similar substances in future. A number of examples are given as illustrations in Plates II., III., IV., V. and VI.

The tabulated measurements carry their own explanation. The specific colour curves are plotted on a chart, in which the ordinates are divided into units corresponding to the divisions of the colour scales, and the abscissæ are divided to represent the measurement of regularly increasing densities.

The principal points of the new theory are combined in the following code of nine laws :—

A Code of Nine Laws which Govern Visual Colour Phenomena.

Nos. 1, 2 and 3 relate to White and Coloured Light.

1. Normal White Light is made up of the six colour-rays Red, Orange, Yellow, Green, Blue and Violet in equal proportions. When these rays are in unequal proportions the light is abnormal and coloured.

2. The particular colour of an abnormal beam is that of the one preponderating ray, if the colour be simple, or of the two preponderating rays, if the colour be complex. The depth of colour is in proportion to the preponderance.

3. The rays of a direct light are in a different condition to the same rays after diffusion, and give rise to a different set of colour phenomena.

Nos. 4, 5, 6 *and* 7 *deal with Limitations of the Vision to appreciate Colour.*

4. The vision is not simultaneously sensitive to more than two colour rays in the same beam of light; the colour of any other abnormal rays being merged in the general luminosity of the beam.

5. The two colours to which the vision is simultaneously sensitive are always adjacent in their spectrum order, red and violet being considered adjacent for the purpose.

6. The vision is unable to appreciate colour in an abnormal beam outside certain limits from two causes:—

(*a*) The colour of an abnormal beam may be masked to the vision from excess of luminosity.

(*b*) The luminous intensity of an abnormal beam may be too low to excite definite colour sensations.

7. The vision has a varying rate of appreciation for the different colours by time, being lowest for red and increasing in rapidity through the spectrum until the maximum rate is reached in violet.

Note.—This varying rate necessitates a time limit for critical observations: five seconds has been adopted, as no variations are perceptible in that time.

Nos. 8 *and* 9 *relate to Colour Constants.*

8. The colour of a given substance of a given density is constant so long as the substance itself remains unaltered.

9. Every definite substance has its own specific rate of colour development for increasing densities.

Past and Present Theories.

Most colour theorists agree on the principle that some colours are primaries and the others, mixtures of primaries, but wide differences exist as to their number and selection, the following six theories probably do not comprise all, but will be sufficient for illustration.

Comprising Primaries.

1. A seven-ray theory	Red	Orange	Yellow	Green	Blue	Indigo	Violet
2. A six-ray „	Red	Orange	Yellow	Green	Blue	..	Violet
3. A five-ray „	Red	..	Yellow	Green	Blue	..	Violet
4. A four-ray „	Red	..	Yellow	Green	Blue	..	..
5. A three-ray „ A	Red	..	Yellow	..	Blue	..	..
6. A three-ray „ B	Red	..	..	Green	..	..	Violet

One of the difficulties which embarrasses the investigating colour student at the outset of his career is the want of a standard of reference, to which the various conflicting theories can be brought for comparison.

A near approach to such a standard is the spectrum from a diffraction grating, where the colours are equidistant. There is, however, no place for mixtures of red and violet, the terminal colours of the spectrum, although these mixtures constitute one-sixth of all distinguishable colours.

The deficiency is made good in the late M. Chevreul's chromatic circle, which is a replica of the diffraction spectrum in circular form, but with a space between the red and violet lines equal to one-sixth of the whole circle, and filled with their graduated mixtures.

Note.—The author has had the pleasure of seeing this table, and although some of the colours were faded, their arrangement is in accord with the chromatic circle figured in this work.

By this arrangement we are able to construct a chromatic circle, within which the primaries of any theory find a place in accord with their natural position in a diffraction spectrum as in Plate VII., where the primaries of the six theories already mentioned are so represented.

Under the generally accepted view that primaries are the simple colours of a system, and all other colours the result of their mixture, we can, by a reference to the chromatic circle, catalogue the theoretical colours which the primaries of each theory are required to produce.

A Seven-Ray Theory.

Primaries.	Theoretical Mixtures.
Orange and yellow	Orange-yellow
Yellow and green	Yellow-green
Green and blue	Blue-green
Blue and violet	Blue-violet
Violet and indigo	Violet-indigo
Indigo and red	Indigo-red
Red and orange	Red-orange

A Six-Ray Theory.

Primaries.	Theoretical Mixtures.
Red and orange	Red-orange
Orange and yellow	Orange-yellow
Yellow and green	Yellow-green
Green and blue	Green-blue
Blue and violet	Blue-violet
Violet and red	Violet-red

A Five-Ray Theory.

Red and yellow	Red-orange Orange Orange-yellow
Yellow and green	Yellow-green
Green and blue	Green-blue
Blue and violet	Blue-violet
Violet and red	Violet-red

A Four-Ray Theory.

Red and yellow	Red-orange Orange Orange-yellow
Yellow and green	Yellow-green
Blue and green	Blue-green
Blue and red	Blue and violet Violet Violet and red

A Three-Ray Theory.

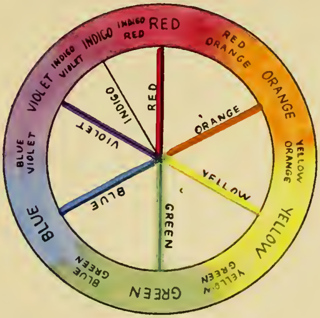
Red and yellow	Red-orange Orange Orange-yellow
Yellow and blue	Yellow-green Green Green-blue
Blue and red	Blue-violet Violet Violet-red

A Three-Ray Theory (Modern).

Red and green	Red-orange Orange Orange-yellow Yellow Yellow-green
Green and violet	Green-blue Blue Blue-violet
Violet and red	Violet-red

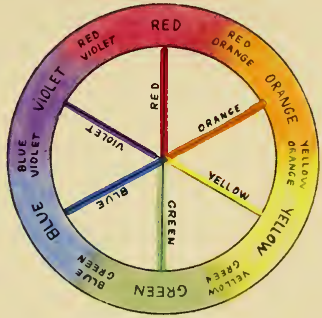
ILLUSTRATING THE POSITION OF THE PRIMARIES
IN RELATION TO THE COLOURS REQUIRED TO BE PRODUCED BY THE THEORETICAL MIXTURES
AND ALSO IN RELATION TO THE CHROMATIC CIRCLE.

A SEVEN RAY THEORY.



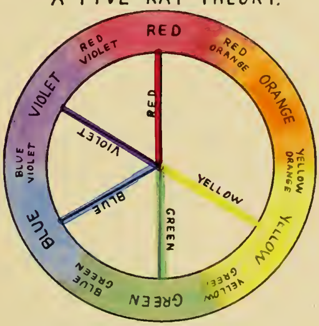
NEWTON.

A SIX RAY THEORY.



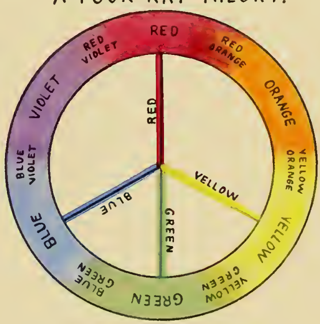
WERNER.

A FIVE RAY THEORY.



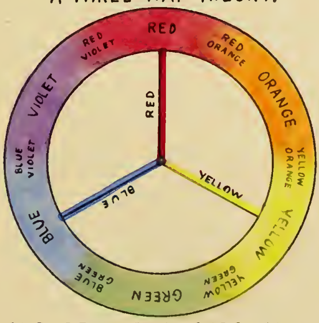
NEWTON (early). HELMHOLTZ (early).

A FOUR RAY THEORY.



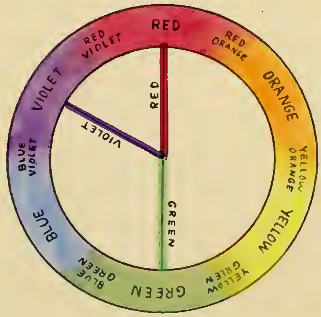
HERING.

A THREE RAY THEORY.



CHEVREUL. BREWSTER. HAY.
REDGRAVE. FIELD

A THREE RAY THEORY.



YOUNG — HELMHOLTZ.

The New Colour Theory.

The basis of the new theory is a beam of white light defined by Law 1 in the code already detailed as being composed of the six primary colours, red, orange, yellow, green, blue and violet, in equal proportions.

The whole six colours are considered as primaries because each can be separately distinguished, the definition of a primary being that it can be separated from all the other colours; with this condition complied with, a normal vision is considered as being furnished with a six-colour perceiving apparatus.

The vision is equally sensitive to the six primaries as visual monochromes, but it is an experimental fact that in most natural and pigmentary colours, they are divisible in the first instance into two classes; one class, orange, green and violet, not being further divisible, are monochromes in the full sense of the term, whilst the other class, red, yellow and blue, are each the middle ray of a trichromatic group as shown in Figs. 4, 5, and 6 in Plate VIII., the two outside rays of each group not being colour evident so long as the trichromatic nature of the group is unbroken. Red, yellow and blue are, therefore, when in this condition, visually monochromes, but structurally trichromes.

This method of analysing a beam of white light into its colour elements is illustrated in Fig. 6, showing the first separation into three triad groups and the groups into three rays.

In consequence of red, yellow and blue having this property of masking their two associated rays, they are called the dominant colours of the system, whilst orange, green and violet are called the subordinates. Each triad group contains one dominant and two subordinates, constituting one half the chromatic circle, whilst the complementary half contains two

dominant and one subordinate. Each triad group has one subordinate ray in common with the adjacent triad group on either side.

This system of trichromatic grouping together, with the order in which the two colours, simultaneously distinguishable under Laws 4 and 5 of the code, fall naturally into symmetrical positions within the precincts of an equilateral triangle, subdivided into four equilateral triangles, as in Fig. 7, where the middle triangle is equally divided to represent the division of white light into the red, yellow and blue triad groups, whilst the three outer triangles represent the division of each group into their three composing colour rays. The bounding lines of the outside triangle represent the subordinate rays, which are common to adjacent triad groups, and form the abscissæ of the series of six charts represented in Plate I. Whilst the perpendiculars from the red, yellow and blue points of the chromatic circle, bisect these lines and form the ordinates, the chromatic circle is added in order to show that the dominant colours of the circle coincide in position with the chart ordinates, and the subordinate colours with the abscissæ.

Representation of Colours in Space of Three Dimensions as Suggested by Dr. Munro.

The relations of the different colours to one another and to neutral tint are, perhaps, best represented to the mind by a solid model, or by reference to three co-ordinate axes, as employed in solid geometry, Fig. 8.

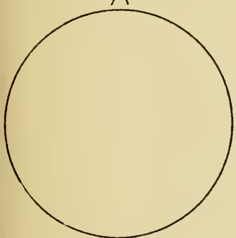
Let the three adjacent edges O R, O B, O Y, of the above cube be three axes, along which are measured degrees of red, yellow and blue respectively, starting from the origin O. Every point in space on the positive side of this origin will then represent a conceivable colour, the constituents of which

PLATE VIII.

NINE CIRCLES ILLUSTRATING THE ANALYSIS OF A BEAM OF WHITE LIGHT INTO THE SIX COMPOSING COLOURS BY THE ABSORPTIVE METHOD

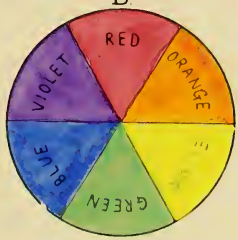
WHITE LIGHT

A



DIVIDED INTO CHROMATIC EQUIVALENTS.

B.



WHOLLY ABSORBED

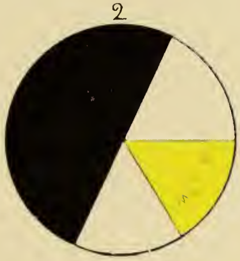
C.

COLOURS OF

THE FIRST DIVISION DEVELOPED BY THE ABSORPTION OF THE THREE COMPLIMENTARIES

1

2

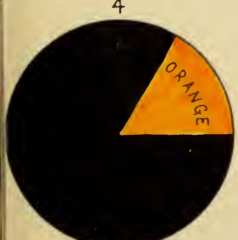


3

COLOURS OF

THE SECOND DIVISION DEVELOPED BY THE ABSORPTION OF THE FIVE OTHER RAYS

4



5

6

in degrees of red, yellow or blue, are measured by the three co-ordinates of the points. Pure reds all lie on the axis O R, pure yellows on the axis O Y, and pure blues on the axis O B. All normal oranges, normal greens, and normal violets lie on the diagonals of the faces of the cubes O O′, O G, O V respectively. Pure neutral tints lie on the diagonal O N of the cube, equally inclined to the three principal axes. Red violets will be found on the plane R O B between O V and O R; blue violets on the same plane between O V and O B; "saddened" red violets all within the wedge or open space enclosed by the three planes, whose boundaries are O B, O V, O N. The other colours, red and yellow oranges, blue and yellow greens, pure, and saddened, are found in corresponding positions in relation to the other axes.

The Colour Scales.

A normal vision has no hesitation in correctly naming the sensation produced by a triad group or by a single ray such as red, green, etc. It can also correctly describe a complex colour sensation by naming the two associated colours such as red-orange, yellow-green, blue-violet, etc.; but when called upon to decide differences in colour depth, it can only do so by using arbitrary terms of no precise scientific value, as light, medium, dark, etc.

This deficiency is because the vision, although automatically sensitive to each colour, has in itself no arrangement for the quantitative definition of colour depth. This want can only be met by co-relating colour sensations to some physical colour constants.

This co-relation has now been effected by a series of glass standard colour scales, which are numerically graded for colour depth, the scales themselves being made into colour constants by co-relation to percentage solutions of such coloured chemi-

cals as copper sulphate, potassium permanganate, potassium bichromate, etc. These substances, as well as many others, are always available for checking the equivalence of the scales, or for recovering the unit if lost.

In experimenting for the best method of constructing scales available for colour constants, the first work was done with taper wedges of coloured glass and taper cells for containing coloured liquids, both being graded to a scale of regularly increasing thicknesses. These proved to be useless for the purpose, not only because the rate of colour increase was never in proportion to the rate of density increase, but also because no two substances are equal in this respect, each having a rate specific to itself.

The spectrum colours were not available for several reasons; first as being unsuitable for critical comparisons under daylight conditions as being too weak except *in camera*; also they were found to be too crowded for the separation of a working area of monochromatic colour, and some corrections would have been necessary for variations in the refractions of the different rays.

On the Equivalence of the Colour Scale.

The method employed for obtaining equality of the unit divisions, and colour equivalence between the different scales was as follows.

Two slips of red glass in a light shade were made exactly equal in colour, and considered as initial units, these were then superimposed and matched by a single glass, which was then considered as of two colour units, this and one of the initial units were superimposed and matched by a single glass of three colour units, and so on, until a progressive red scale was constructed, ranging in intensity from 0·06 to 20 units.

FIG. 6

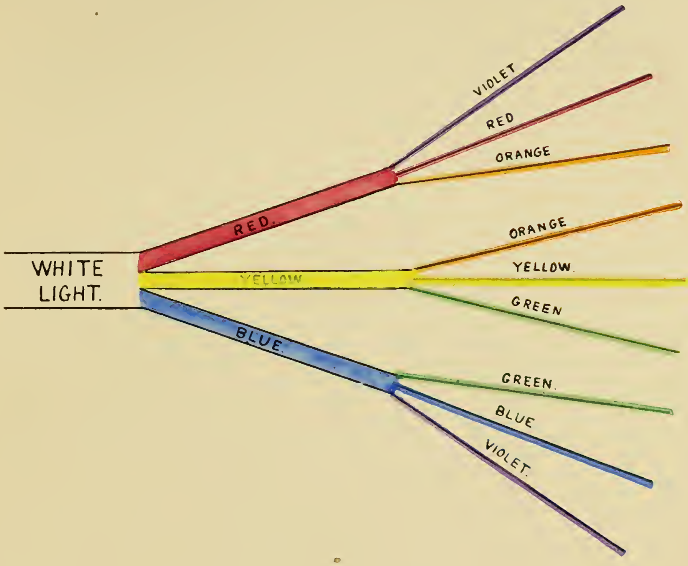

WHITE LIGHT.
RED.
YELLOW
BLUE.
VIOLET
RED
ORANGE
ORANGE
YELLOW.
GREEN
GREEN.
BLUE
VIOLET.

FIG 7

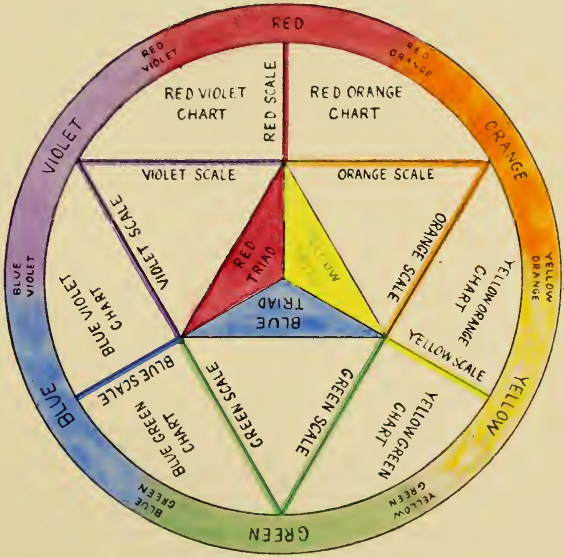

RED
RED ORANGE
ORANGE
YELLOW ORANGE
YELLOW
YELLOW GREEN
GREEN
BLUE GREEN
BLUE
BLUE VIOLET
VIOLET
RED VIOLET
RED SCALE
RED VIOLET CHART
RED ORANGE CHART
VIOLET SCALE
ORANGE SCALE
VIOLET SCALE
ORANGE SCALE
YELLOW ORANGE CHART
BLUE VIOLET CHART
RED TRIAD
BLUE TRIAD
YELLOW SCALE
BLUE SCALE
GREEN SCALE
GREEN SCALE
BLUE GREEN CHART
YELLOW GREEN CHART

FIG. 8

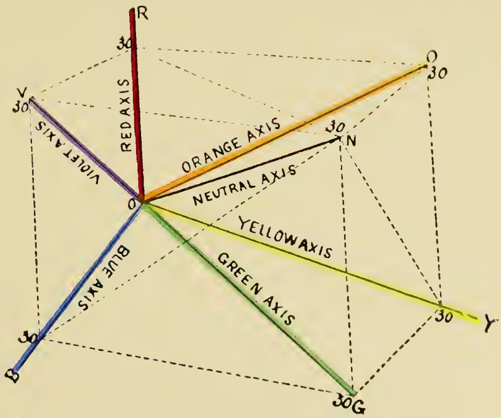
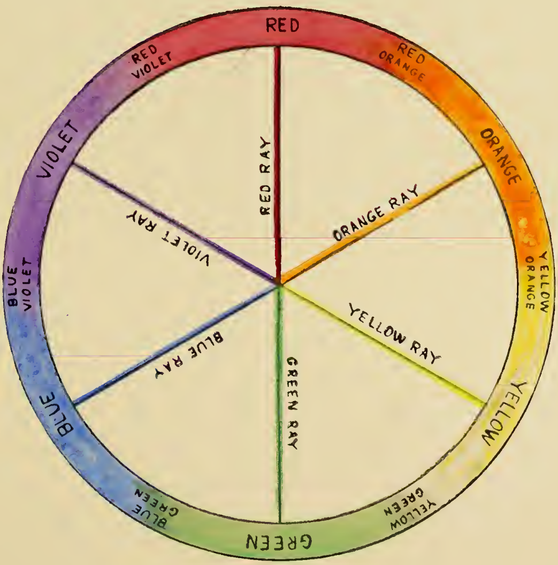


FIG 9
CHROMATIC CIRCLE.



The yellow and blue scales were similarly constructed, taking care that their similar unit values were in colour equivalence with the red units, the test of equivalence being, that when equal units in the three scales were superimposed against a white light, a neutral grey was transmitted, in which no trace of colour could be perceived by the common consent of the whole staff of trained observers. The scales were then considered as in colour equivalence with each other. The system of cross-checking was so elaborate that nearly four years was occupied in the work before the scales were passed as satisfactory.

It may be urged that the unit is arbitrary, but this applies also to the unit of any other standard scale, it is sufficient that the essential conditions of a philosophic scale are complied with, in that the divisions are equal, and the unit is recoverable.

On Colour Perception and Colour Nomenclature.

The diagrams in Plate VIII. illustrate that a single glass colour transmits a triad group as a visual monochrome by absorbing the three complementary rays, that two equal glass colours transmit a true monochrome by absorbing the other five rays, and that three equal glass colours absorb all light, necessarily in each case up to the unit value of the glasses used.

The sensitiveness of the vision for complex colour is limited to the simultaneous perception of two colours in the same beam of light as defined by Law 4 in the code; they are however, discernible in any proportion with each other.

The order of complexity is defined by Law 5, and is illustrated by the chromatic circle, Fig. 9, showing any two colours which are simultaneously distinguishable, as adjacent to each other.

It is also illustrated by the series of six charts in Plate I., where in each case the two associated colours form one chart.

The demonstrated fact that there are only two colour factors in a complex colour, but which may be modified by a light factor, permits the construction of a scientific nomenclature by means of which the most complex colour sensation can (after co-relation to the colour scales already described) be defined by two colour terms and one light term.

The colour terms used are those of the six primaries, red, orange, yellow, green, blue and violet; the use of a single term denotes a simple colour, and the use of two terms, a complex colour; the light terms used are black and light.

A simple or complex colour may be of standard brightness, in which case no light term is required.

When a colour is less bright than the standards, it is caused by a greater absorption of light, and is equivalent to the addition of black in pigmentary mixtures, the value is, therefore, termed black units, and is added to the descriptive colour terms.

When a colour is brighter than the standards, it is caused by a greater reflection or transmission of light; this is measured by the standard glasses, and added to the descriptive colour terms as light units.

On Colour Curves as a Means of Identifying Specific Substances.

A colour curve is a graphic method of representing the rate in changes of colour arising from increasing densities, changes of condition, fading, or any other cause.

The factors for constructing a colour curve are derived from a table of colour measurements at different densities, or other factors.

The chart to be used must be one of the series of six, figured in Plate I., the special chart being that one whose two lines correspond in colour to those of measurement to be plotted.

The position of each measured sensation is indicated on the chart at that point, where perpendiculars drawn through their unit values meet, as already described on page 14; the points are then connected by lines, and the resultant curve is specific for that particular substance, affording a means of identifying similar substances in future. The figures on Plates II. and IV. are examples.

When a colour factor changes with increasing density, the chart is doubled by drawing the new colour line at the point of change, parallel to the colour line it displaces. All the figures on Plate V., and Figs. 1, 2, 4, and 5 on Plate VI. are examples.

When a light factor is present in the sensation, its value must be written at the points of measurement.

It is sometimes desirable to know the change of each colour factor separately, when a supplementary form of chart is used, in which the ordinate represents the scale of units irrespective of colour, and the abscissæ a scale of increasing densities, time or any other factor, which may be required.

The unit values of each colour factor are plotted on the chart and the points of similar colours connected by lines, the resultant curves give the required information. Examples occur in Plates II., III. and IV.

When a light factor is present in the sensation, it may be indicated by a separate curve, as in Plate II., Figs. 2 and 5, Plate III., Figs. 1, 2 and 5, and Plate IV., Figs. 1 and 2.

The accordance of the theory explained, with the practical work carried on by means of the correlated colour scales, is demonstrated by their constant agreement, and may be reviewed by again referring to Fig. 7.

This figure illustrates the analysis of a beam of white light, first into three triad groups, and the groups into their constituting colour rays, as represented by the lines of the three outer equilateral triangles; around the triangles are grouped the series of six charts figured on Plate I. and used in finding the position of the measured colours, and for plotting the curves. The colour lines of the charts are in strict relation to their theoretical colour positions in the surrounding chromatic circle.

The capacity of these charts for charting colour sensations is limited only by the power of the vision for discriminating small differences between the divisions of the colour scales.

The number and variety of colour sensations separately distinguishable in a beam of diffused white light of 20-light units intensity, is limited only by the power of the vision for differentiating between the divisions in the colour scales, and a normal vision has no difficulty in distinguishing, measuring, and therefore charting 61,525,998 separate colour sensations. This number and classification is set out in the following table:

Simple colour sensations	2,958
Complex "	518,544
Saddened "	61,004,496
	61,525,998

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Quantitative Colour Diagram.